UCRL-CONF-207723

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Insights into the Dynamic Response of Tunnels in Jointed Rocks

F. E. Heuze

November 5, 2004

2005 U.S. Rock Mechanics Symposium
Anchorage, AK, United States
June 25, 2005 through June 29, 2005

INSIGHTS INTO THE DYNAMIC RESPONSE OF TUNNELS IN JOINTED ROCKS

Francois E. Heuze
Lawrence Livermore National Laboratory, Livermore, CA

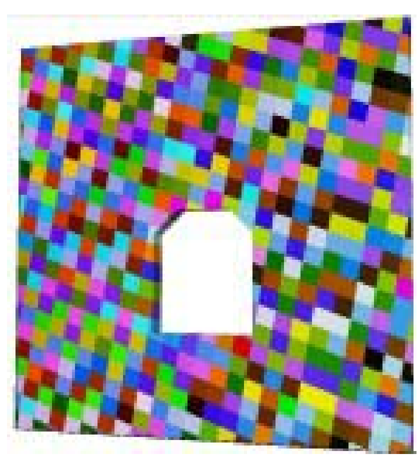
Abstract

Tunnels in jointed rocks can be subjected to severe dynamic loads because of rock bursts, coal bumps, and large earthquakes. A series of 3-dimensional simulations was performed, based on discrete element analysis to gain insights into the parameters that influence the response of such tunnels.
The simulations looked at the effect of joint set orientation, the effect of joint spacing, the effect of pulse shape for a given displacement, and the influence of using rigid versus deformable blocks in the analyses.
The results of this modeling were also compared to field evidence of dynamic tunnel failures. This comparison reinforced the notion that 3-dimensional discrete element analysis can capture very well the kinematics of structures in jointed rock under dynamic loading.

Overview

A series of tunnel-in-rock-island calculations was performed with the LDEC 3-dimensional discrete element code [1] to examine several issues: the influence of joint set orientation and of joint spacing on tunnel stability, the influence of pulse shape for a given displacement, the effect of using rigid versus deformable blocks in LDEC, and the adequacy of LDEC models to represent actual tunnel failures.
The basic two rock-island configurations are shown in Figure 1. The rock island is 16mx16mx1m. The tunnel is 4-m wide by 5-m high. The rock joint spacing is 0.7m in the plane of the figure and there is one block in the thickness of the island. The simulations were performed in plane strain.

Geology 1 (513 blocks)



Geology 2 (519 blocks)

Figure 1. Basic joint geometries for LDEC calculations

Twenty-seven different cases were calculated, corresponding to variations in geology, in joint orientation, in level of loading, and in rock bolting (Figure 2). Table 1 summarizes the attributes of the 27 cases.

Table 1. Summary of the Main Features for the 27 Simulations

Case	Geol.	Bolts	Stress (MPa)	Displ. (cm)
A070c1a	1	No	0	0
A070c2	1a	No	0	0
A080c1	1	Yes	0	0
B070c1	1	No	3	1.4
B071c1	3	No	3	1.4
B072c1a	5	No	3	1.4
B073c1a	7	No	3	1.4
B074c1	9	No	3	1.4
B080c11a	1	Yes	3	1.4
B082c1	5	Yes	3	1.4
C070c1a	1	No	6	2.8
C080c1a	1	Yes	6	2.8
C090c	2	No	6	2.8
D090c	2	No	12	5.6
E090c	2	No	18	8.4
F090c1	2	No	24	11.2
G090c11	2	No	30	14.0
G090c2	2a	No	30	14.0
G091c1a	4	No	30	14.0
G092c1a	6	No	30	14.0
G093c1a	8	No	30	14.0
G094c1a	10	No	30	14.0
G101c0	4	Yes	30	14.0
G103c1a	8	Yes	30	14.0
G104c	10	Yes	30	14,0
H090c1	2	No	36	16.8
I090c1	2	No	45	21.0

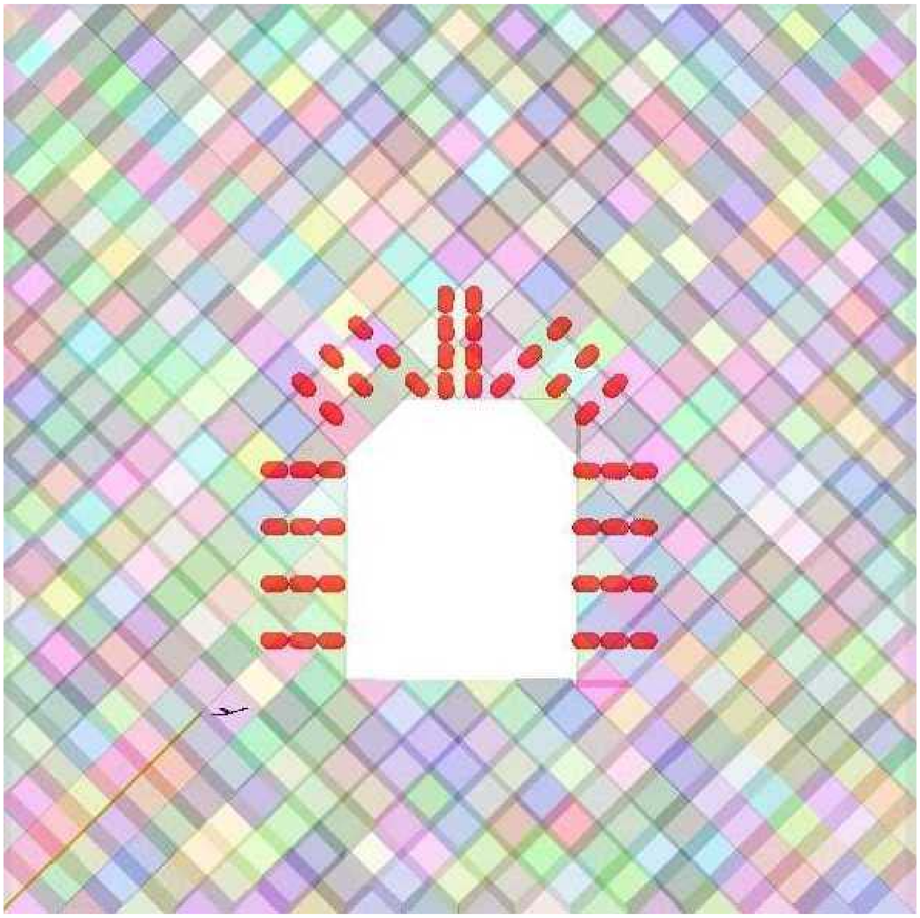
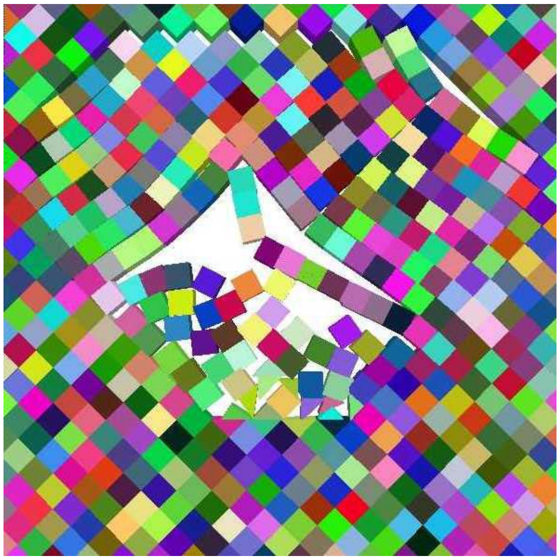


Figure 2. Rock Bolt Pattern for Reinforced Tunnels

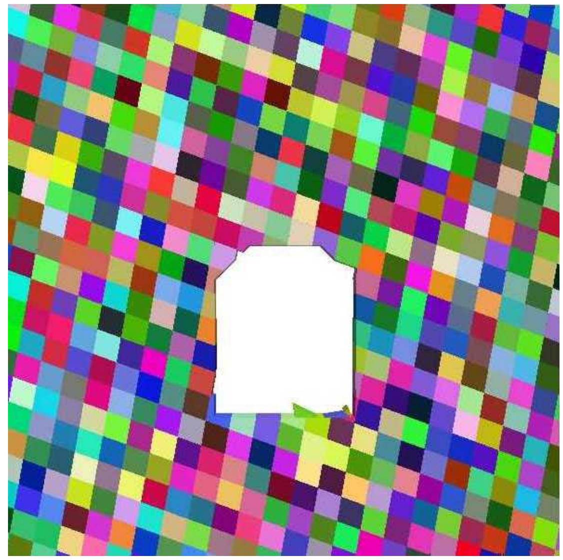
The odd-numbered geologies are variations on geology 1, and the even-numbered are variations on geology 2. Cases A were under gravity loading only. For case B through I, loading was under the form of a triangular velocity pulse applied at 45^o to the top and left boundaries of the rock island. The rise time and decay times were 4 ms and 16 ms respectively for cases B through F, and 5 ms and 20 ms respectively for cases G through I. The peak displacement created by the velocity pulse is shown in Table 1, as well as the corresponding peak stress. The island was put under a 2MPa uniform all-around static pressure. The tunnel was excavated under that initial stress at 50ms, and the pulse was applied to the boundaries at 100ms.

Effect of Joint Orientation on Tunnel Hardness

A first comparison was made for the same tunnels in geologies 1 and 2 (Figure 3). It is shown that joint system orientation alone can have a considerable effect on tunnel hardness. With the same number of joint sets, the same joint spacing, the same rock material properties, the same joints properties, the same in-situ stresses, and the same tunnel geometry, the tunnel hardness in geology 2 is over 15 times that of its hardness in geology 1.



a) Tunnel in geology 1, under a 3-MPa pulse



b) Tunnel in geology 2, under a 45-MPa pulse

Figure 3

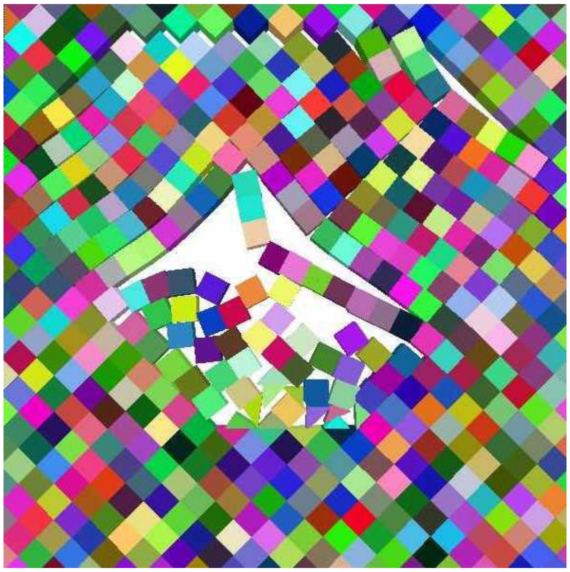
The effect of joint orientation was further examined by varying the dip angle of a single joint set in geologies 1 and 2, under gravity loading only. Figure 4 shows the results for variations from geology 1, and Figure 5 from geology 2. For these two geologies, the tunnel stability is greatly enhanced when joint dip angle is reduced. This is a common observation made underground, in jointed rock formations.

Effect of Joint Spacing on Tunnel Hardness

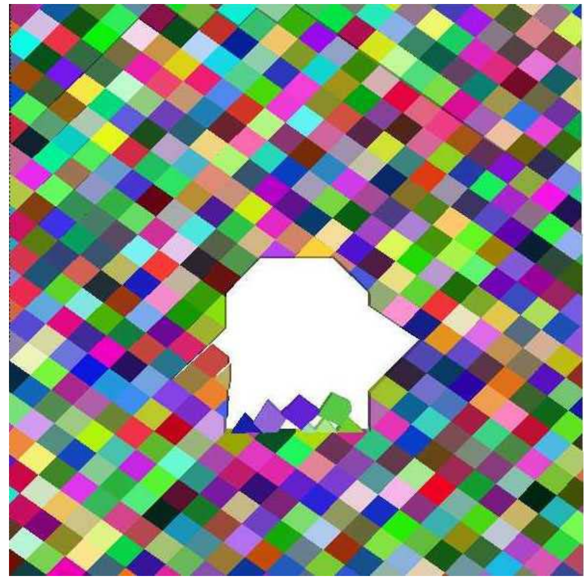
Two comparisons are shown in Figure 6 for cases where the joint spacing has been reduced from 70cm to 35cm in geologies 1 and 2. As known experimentally, closer joint spacing can dramatically decrease tunnel stability.

Comparison of Rigid-Block and Deformable-Block LDEC Results

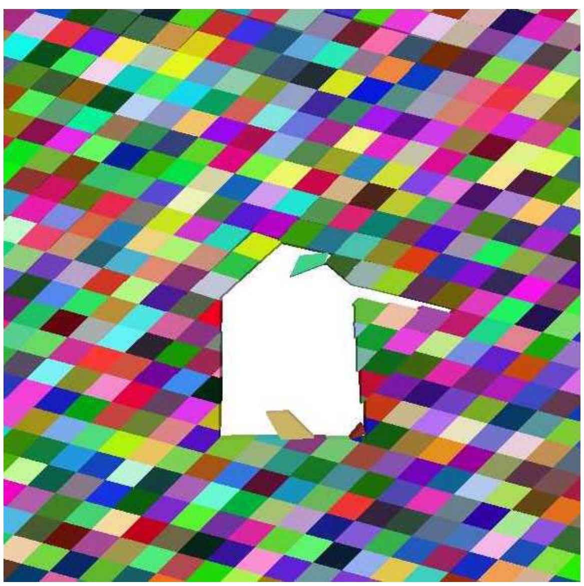
Because deformable-block simulations can take several times the computing time of rigid-block calculations, there is motivation in modeling with rigid blocks if possible The 27 cases of Table 1 were run with rigid blocks and with deformable blocks. In 22 cases the tunnel response was identical. In 2 cases damage was higher in the deformable-block model, and in 3 cases in the rigid-block model. Results of these 5 cases are compared in Figure 7. It is concluded that there does not seem to be a systematic difference between the two approaches, and that the results are generally equivalent. This highlights the fact that geological discontinuities exert a controlling influence on rock mass response. Thus, in jointed rock masses rigid-block calculations will generally be preferred since they are much faster than those with deformable blocks, while appropriately representing the kinematics of jointed media.



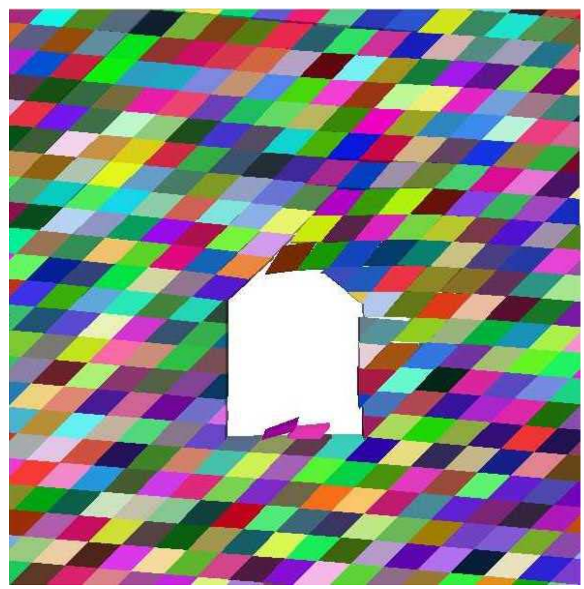
a) Joint set 2 at 45-degrees dip angle



b) Joint set 2 at 35-degrees dip angle

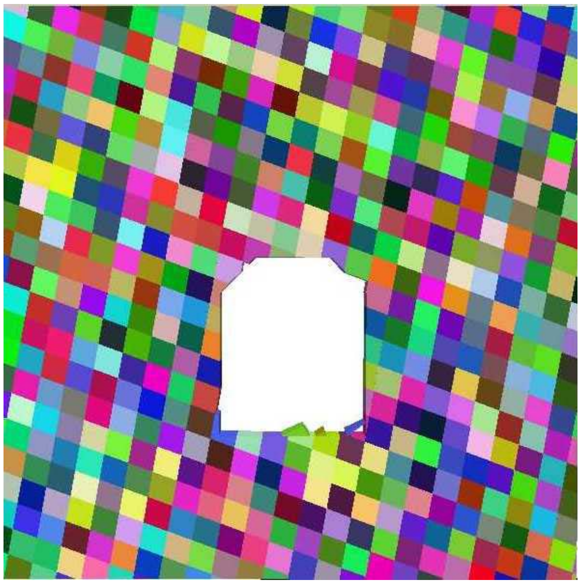


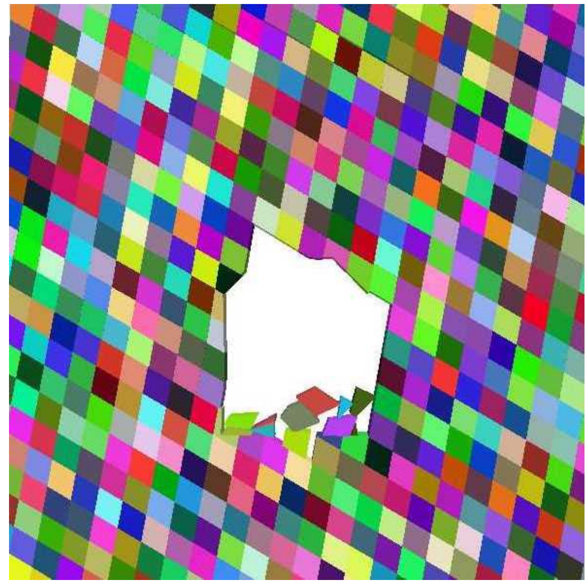
c) Joint set 2 at 15-degrees dip angle



d) Joint set 2 at 5-degrees dip angle

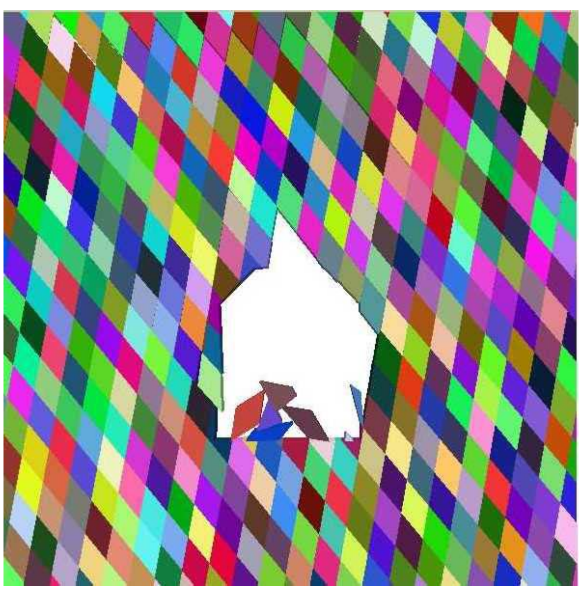
Figure 4. Tunnel in different variations of geology 1; gravity loading only.





a) Joint set 2 at 20-degrees dip angle

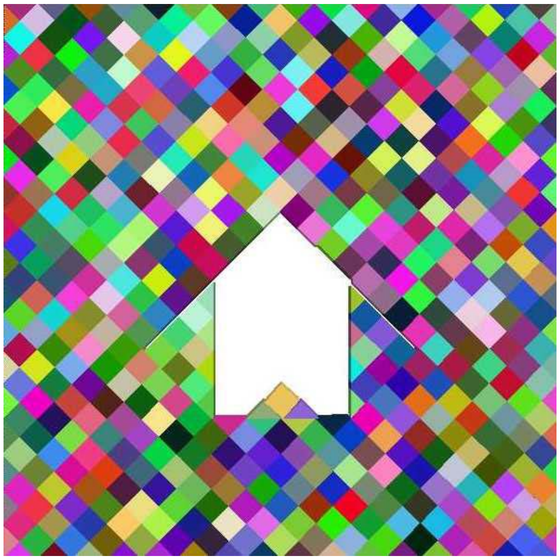
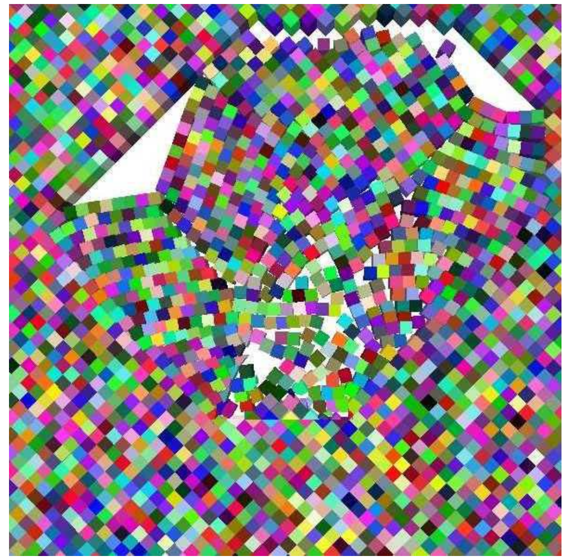
b) Joint set 2 at 30-degrees dip angle



c) Joint set 2 at 50-degrees dip angle

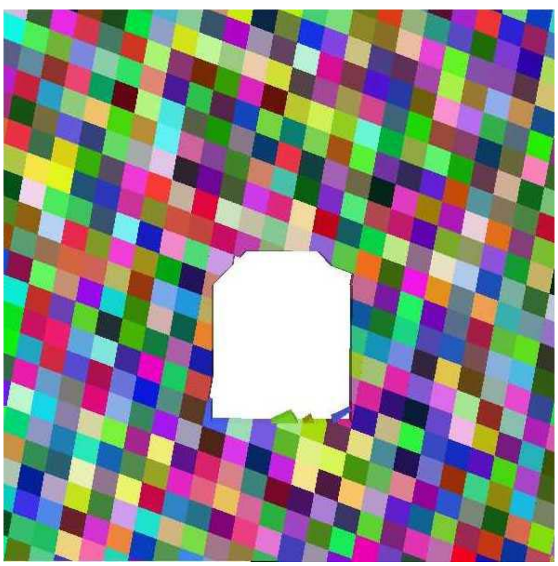
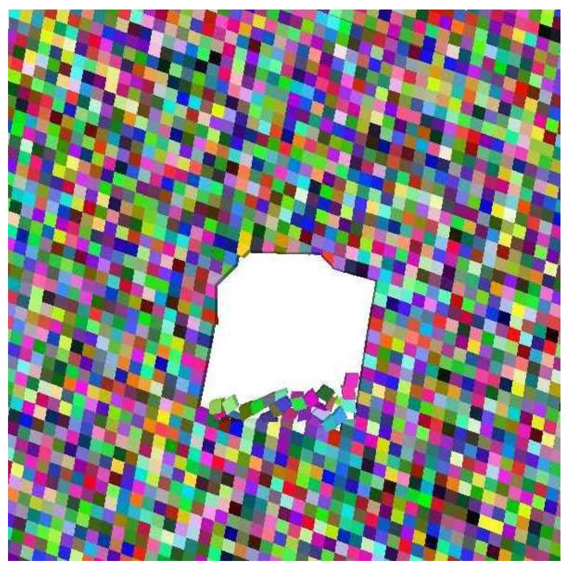
d) Joint set 2 at 60-degrees dip angle

Figure 5. Tunnel in different variations of geology 2; gravity loading only

Joint spacing 70cm   Joint spacing 35cm

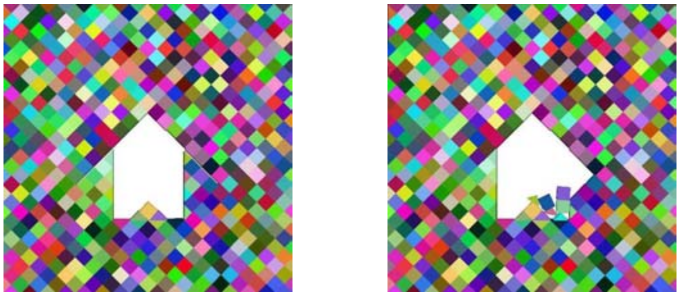
a) Tunnel in geology 1 under gravity loading

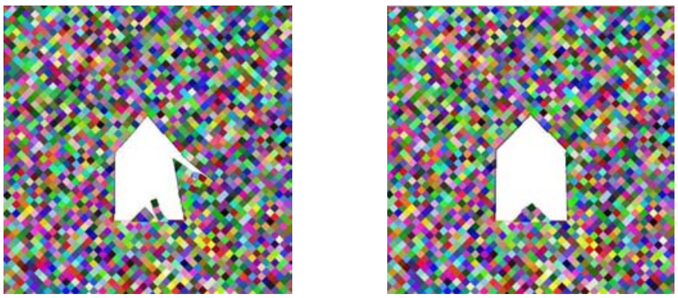
Joint spacing 70cm   Joint spacing 35cm

b) Tunnel in geology 2 under 30-MPa pulse

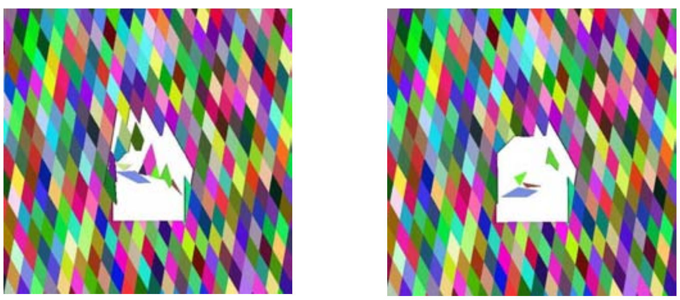
Figure 6. Effect of Joint Spacing on Tunnel Stability



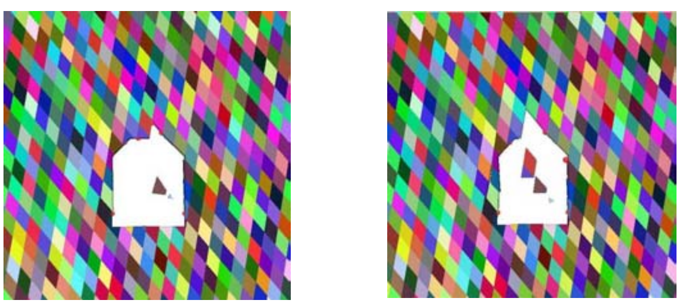
a) Case A070-1. Geology 1.
Joint spacing 70cm.
No pulse



b) Case A070-2. Geology 1.
Joint spacing 35cm
No pulse



c) Case G094. Geology 10.
30-MPa pulse



d) Case G103. Geology 8.
30-MPa pulse

e)

Case G104. Geology 10.
30-MPa pulse

Figure 7. Cases where there is a difference between LDEC results with rigid blocks (left column) and deformable blocks (right column).

Effect of Pulse Shape for a Given Total Displacement

The stability of a tunnel may be related to the total displacement due to the ground shock, compared to the mean joint spacing. In that case, the effect on the tunnel would be independent of the shape of the velocity pulse that creates such a total displacement. To test that hypothesis, a series of calculations was run on for a displacement of 12.5cm corresponding to Case1f1. The pulses are shown in Figure 8; the peak velocity varies between 1 and 20m/s and the duration varies between 250 and 12.5ms. The results are shown in Figure 9.

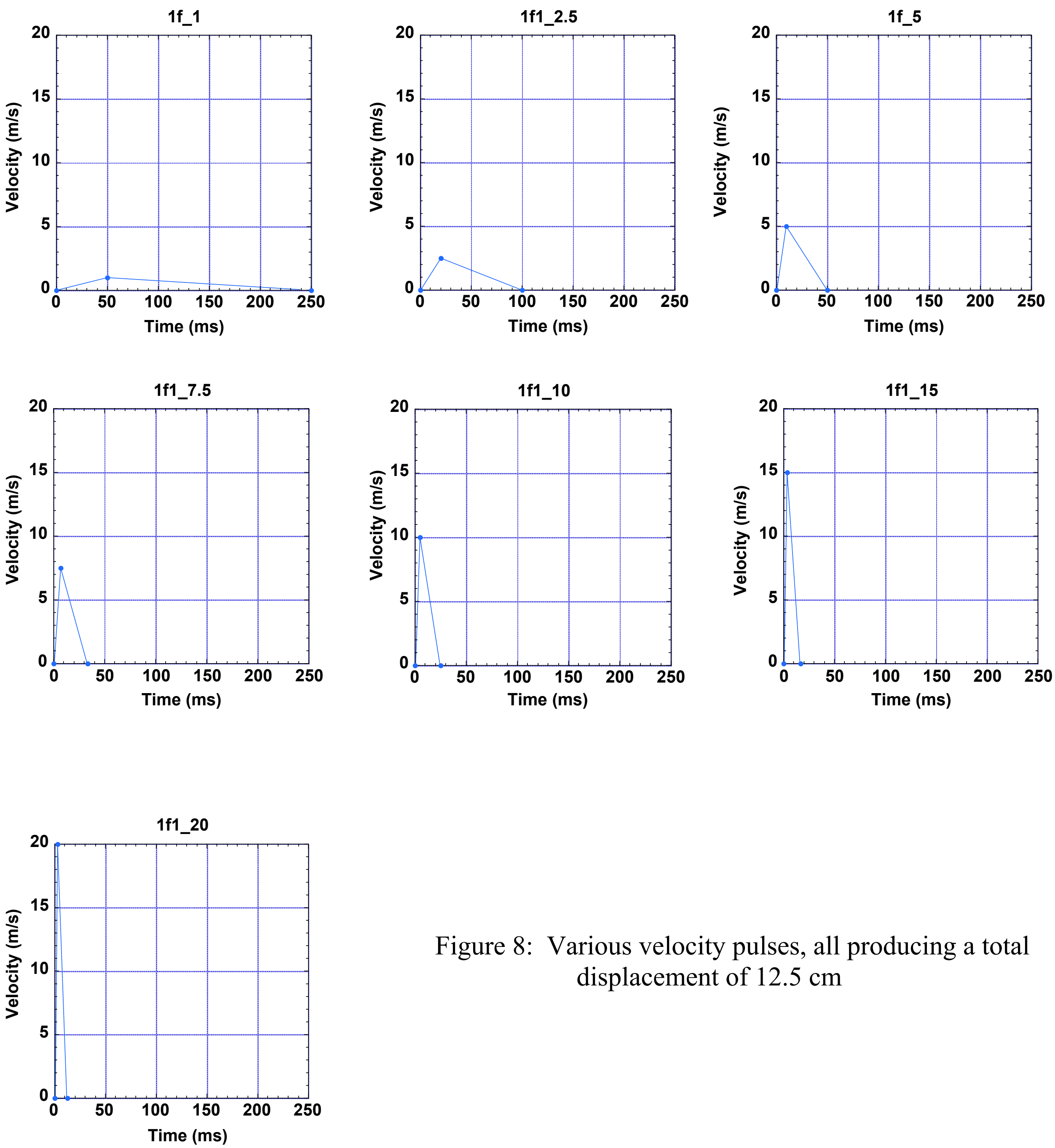
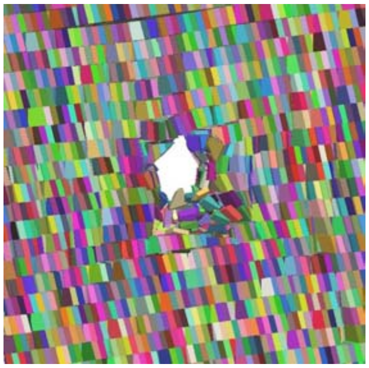
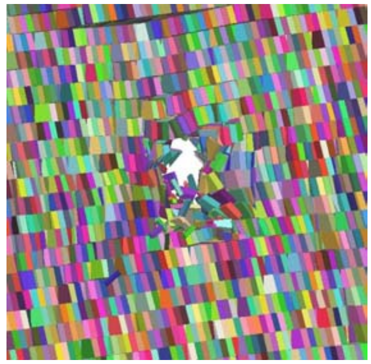


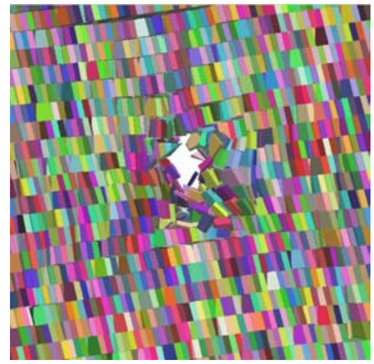
Figure 8: Various velocity pulses, all producing a total displacement of 12.5 cm



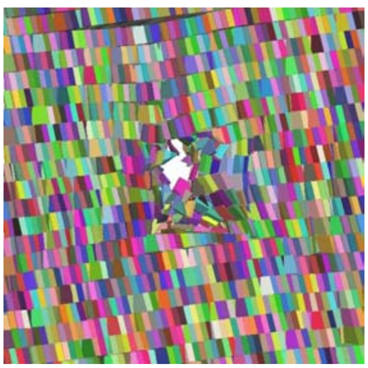
Vpeak = 1m/s



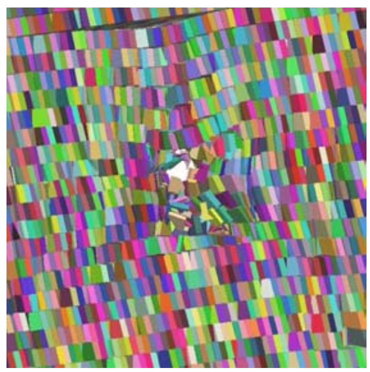
Vpeak = 2.5m/s



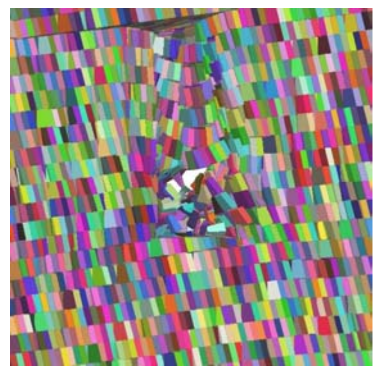
Vpeak = 5m/s



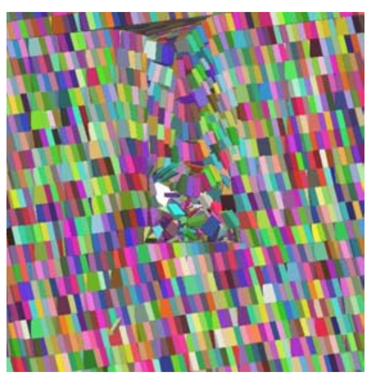
Vpeak = 7.5m/s



Vpeak = 10m/s



Vpeak = 15m/s

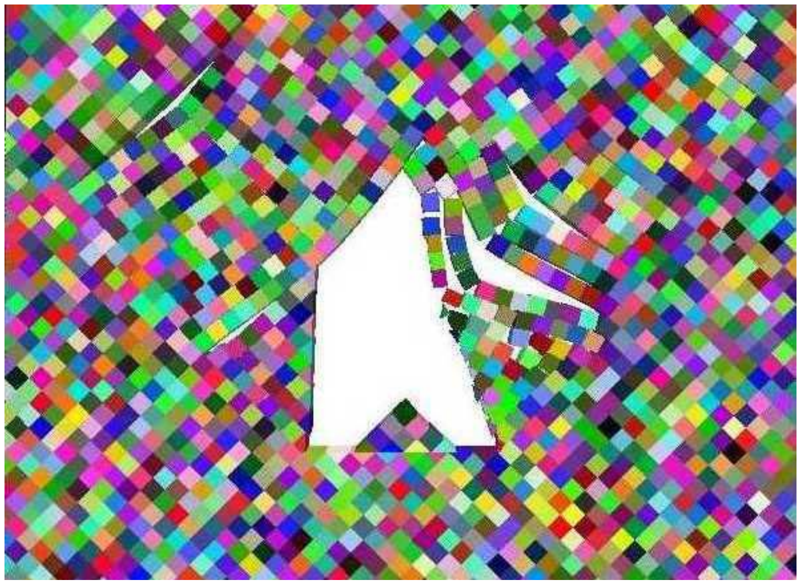


Vpeak = 20m/s

Figure 9: For the same total displacement field, the tunnel destruction occurs for a peak velocity of 2.5m/s or above.

LDEC Simulations Compared to Actual Tunnel Failure Cases

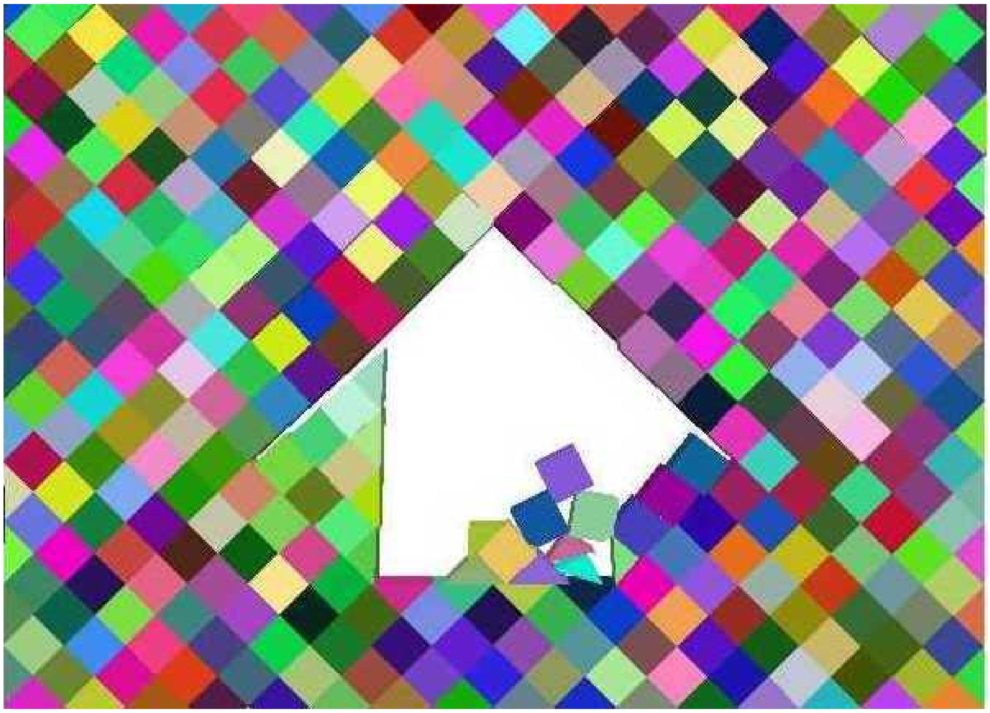
Clearly, it is essential to assess whether such simulations realistically relate to real-life tunnel behavior. To that effect, the author selected from his files several examples of tunnel failures to be compared to the LDEC results. The comparisons, shown in Figures 8 through 10, indicate that these discrete element analyses capture very well the kinematics of tunnel failures under dynamic loading.



LDEC simulation showing buckling of thin rock layers

Ground failure in a Belgian coal mine, after a coal bump. The buckling of layers has been frozen in time and space by the steel support.

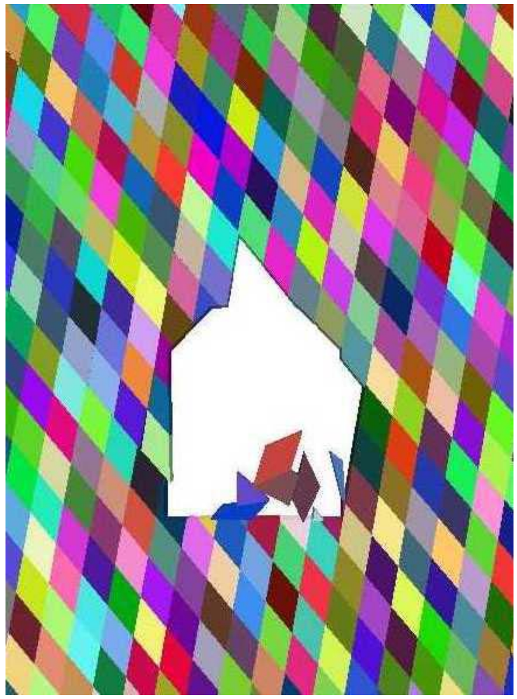
Figure 8



LDEC simulation showing a fairly symmetrical roof failure

Ground failure in a South African gold mine under a rock burst
(Courtesy of D. Ortlepp, 2003)

Figure 9



LDEC simulation showing a non-symmetrical roof failure controlled by jointing

Asymmetrical roof failure in a South African gold mine under a rock burst
(Courtesy of D. Ortlepp, 2003)

Figure 10

References

1. Morris, J. P., Rubin, M. B., Blair, S. C., Glenn, L. A., and Heuze, F. E. "Simulations of Underground Structures Subjected to Dynamic Loading, Using the Distinct Element Method", Engineering Computations, v. 21, n. 2/3/4, pp. 384-408, 2004.

Acknowledgments

This work was performed by the UC Lawrence Livermore National Laboratory, under Contract W-7405-ENG-48 with the U.S. Department of Energy.